

About Impedance-Matching Circuits

What impedance matching means, and which circuits do the job.

H. Ward Silver, NØAX

Impedance matching is a common topic wherever RF is found. This article will explain what impedance matching means and what we accomplish by doing it, with an overview of the components and circuits that do the job. A future article will cover transmission-line techniques, including antenna feed-point matching.

Impedance Explained

Most hams are already familiar with mechanical impedance matching — you can think of impedance as the ratio of “how hard you push” to “how much you get.” An example is the ratio of torque to the rate of rotation in response. If a car is just starting to

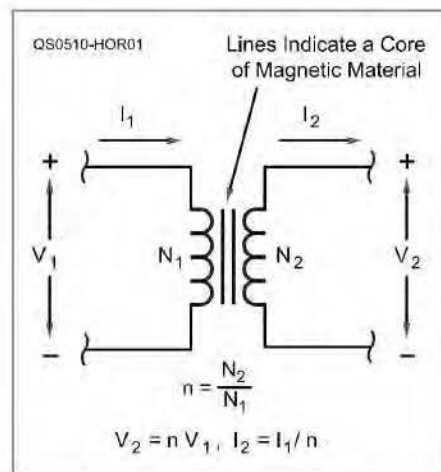


Figure 1 — The basic voltage and current relationships in a flux-coupled transformer are controlled by the secondary-to-primary turns ratio, n .

move, high applied torque but slow rotation means the wheels present a high impedance to the drive shaft. At highway speeds, the engine is running at about the same speed, but the wheels are turning a lot faster — the impedance is lower.

Electrically, voltage is how hard you push and the resulting current is how much you get. So, electrical impedance Z is the ratio of voltage V to current I ; $Z = V/I$ and it's measured in units of ohms, Ω . Voltage and current can be simple magnitudes like 10 V or 20 mA, so that $Z = 10 \text{ V}/0.02 \text{ A} = 500 \Omega$.

In an RF system where reactance is usually present, it's important to include phase in the calculation so

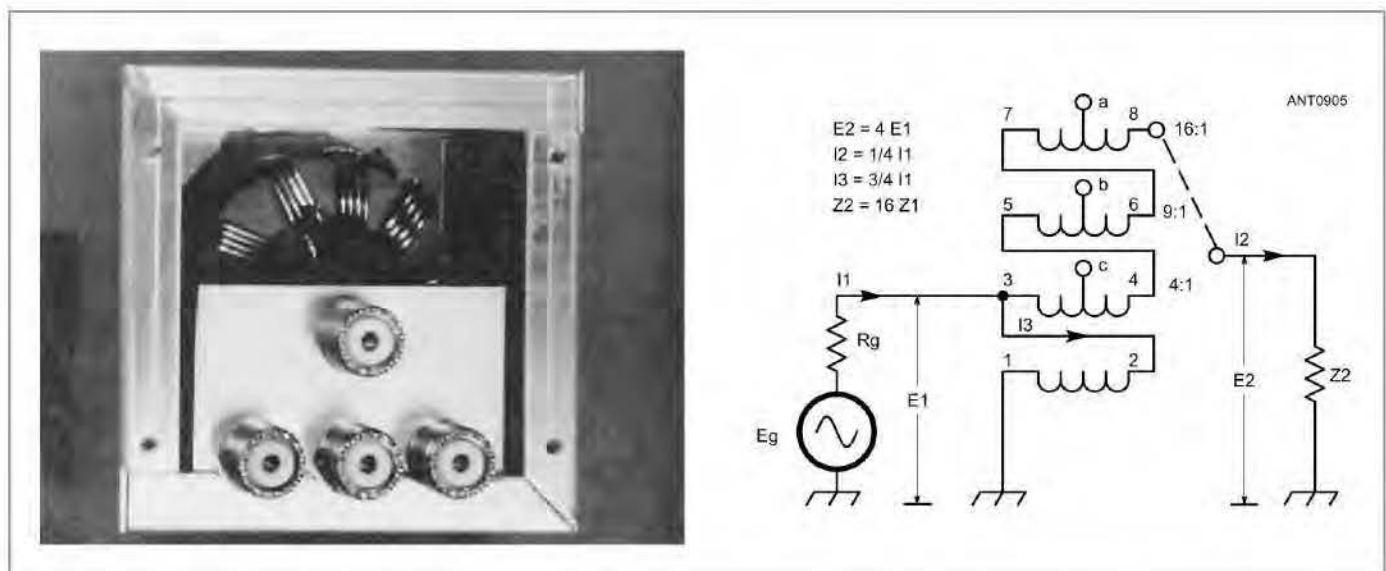


Figure 2 — A four-winding broadband transformer matches impedances with ratios of 4:1, 9:1, and 16:1. A tapped connection can match ratios between 1:1 and 16:1.

that impedance becomes a complex number such as $47 - j80 \Omega$. The sign of the reactance indicates whether it is inductive (positive) or capacitive (negative). As reactance changes with frequency, impedance does too.

Converting Impedance

When we talk about “matching” impedance, what we’re really talking about is converting impedance from one ratio of voltage and current to a different ratio, while losing the least amount of power in the process. All the methods we’ll cover in this article are just ways of changing V/I from one value to another.

Returning to the mechanical analogy, you use an impedance converter every time you drive your car. The transmission is a set of gears that convert the torque-to-rotation rate ratio at the engine’s output to a different ratio at the drive shaft. By selecting different gear ratios, the transmission allows your engine to supply power at an optimum torque-to-rate of rotation, even though the car’s speed may be anything from barely moving (requiring a low gear ratio) to speeding ticket-worthy (at a higher gear ratio). The only power lost is from friction in the gears and bearings, so input power is almost the same as output power — just at a different impedance.

Why Match Impedances?

You can think of an impedance-matching circuit as a sort of electrical gearbox. The combination and connections of components make up the gears that transfer power from input to output. The goal is the same as a mechanical gearbox — maximizing power transfer from the source to the load or allowing a source to generate power at an optimum combination of voltage and current.

Solid-state transmitters are particularly sensitive to load impedance. Impedances far from the 50Ω most transmitters expect can raise voltages or currents in the output transistors. Protective circuits reduce drive power

to the amplifier stage until voltages and currents are within safe limits. This also reduces the bandwidth over which your transmitter will output full rated power. Matching the feed-line impedance to the specified 50Ω keeps your transmitter happy!

Transformers with Cores

Any method of changing the combination of V and I converts one value of impedance to another. Not all methods are suitable for all uses, of course. The following sections will describe common methods and what they are best for.

The word “transformer” is a bit over-used, so we have to be careful about what type. Transformers in this section have primary (input) and secondary (output) windings. (Transformers “work backwards,” too, so the designation of the windings as input or output applies mostly to voltage and current ratings.) Because they use a magnetic field to transfer energy, these are *flux-coupled transformers*. Power is transferred through the core of the transformer as magnetic energy. (*Transmission line transformers* use feed lines wound on a core, but the energy is not transferred *through* the core.) Cores can be magnetic (ferrite, powdered iron) or nonmagnetic (air), depending on how the transformer will be used.

Flux-coupled transformers are very much like two gears transferring power from one shaft to another. The ratio of gear speeds (current) and the ratio of input and output torque (voltage) are controlled by the ratio of teeth on the gears (secondary-to-primary turns ratio, n). The basic voltage and current relationships in a flux-coupled transformer are shown in Figure 1.

Assuming power is being transferred from the primary (input) circuit to the secondary (output) circuit, the impedance presented to whatever is connected to the input winding is $Z_{pri} = V_{pri} / I_{pri}$. The output winding acts like an impedance of $Z_{sec} = V_{sec} / I_{sec}$. From the voltage and current relationships in Figure 1, we also know that $Z_{sec} / Z_{pri} = n^2$. If $n = 2$, the Z ratio is 4; $n = 3$, the Z ratio is 9, etc.

In RF applications, the core material is usually ferrite or powdered iron because these materials can store and transfer nearly all of the RF energy and they work well at high power levels, dissipating little energy as heat. Because they work over a wide frequency range, these are considered *broadband transformers*. If there is no direct or *galvanic* connection between the two windings, this can also act as an *isolation transformer* to block common-mode current.

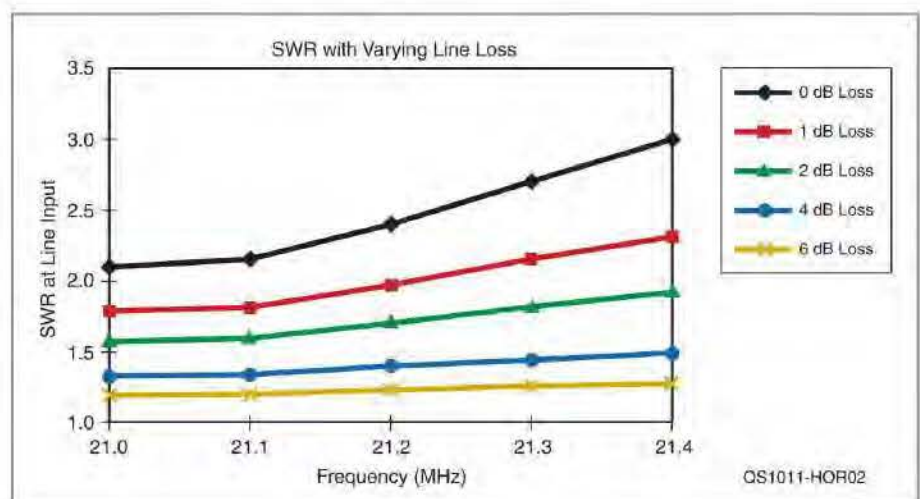


Figure 3 — Increasing feed-line loss reduces SWR at the input to the line. The top curve also represents SWR at the antenna.

Figure 2 shows a four-winding broadband transformer with impedance transformation ratios of 4:1, 9:1, and 16:1. If the windings are tapped, even more ratios are available.¹ This is an example of an *un-un* transformer where both the input and output circuits are *unbalanced*, meaning that they have a common connection to the system's reference voltage (i.e. ground). A transformer can also act as a *balun* which transfers power between a *balanced* feed line or load (both conductors are symmetric with respect to ground) and an *unbalanced* system.

Resistive Matching

Another way of matching impedances is just putting a resistance in series or parallel with the impedance to be matched. If you want to match, say, 18 Ω to 50 Ω , put a 32 Ω resistor in series with it. Or if you have 100 Ω that you want to turn into 50 Ω , add 100 Ω in parallel.

Resistive matching is cheap and very broadband but it has the drawback of

dissipating power. In the 18 Ω example, for every watt of power that gets to the 18 Ω impedance, 1.8 W is dissipated by the 32 Ω resistor which is a 4.4 dB loss from the power source's point of view. The popular TFTD folded dipole uses a high-wattage resistor in a similar way to reduce or "swamp out" SWR variations at the feed point, for example.

You can use an attenuator to match impedances if you are willing to dissipate some power. A good example is the use of a 50 Ω attenuator at the output of a signal generator. The attenuator reduces impedance variations that can upset the signal generator's output calibration. T- and Pi-network attenuator "pads" can also be used.²

Another example is feed-line loss which reduces SWR at the transmitter. Figure 3 shows the effect of feed-line loss on SWR.³ Really long runs of coax make terrific dummy loads and are often used as loads at microwave frequencies.

Reactive Matching

What we usually think of as impedance matching is *reactive matching* that uses L and C components. These create phase shifts in ac voltages and currents, which combine to create a new combination of voltage and current. Reactance changes with frequency so the circuit has to be tuned to perform the impedance conversion at each different frequency.

There are a number of different circuits commonly used for reactive impedance matching; L-, Pi-, and T-networks. "Network" is just a fancy name for "circuit." All three of these networks are covered in detail, including design equations, in *The ARRL Handbook* and in an excellent three-part series of QST articles by George Grammer, W1DF, in 1957.^{4, 5}

L-networks

Figure 4 shows four common L-network circuits you can use. Each configuration can match exactly half of all possible impedances. The white regions on the abbreviated Smith chart show all the different impedances (Z_{LOAD}) a particular circuit can match to the desired impedance (Z_0) at the center of the chart.^{6, 7, 8} Note that charts are symmetrical if the network input and output are reversed.

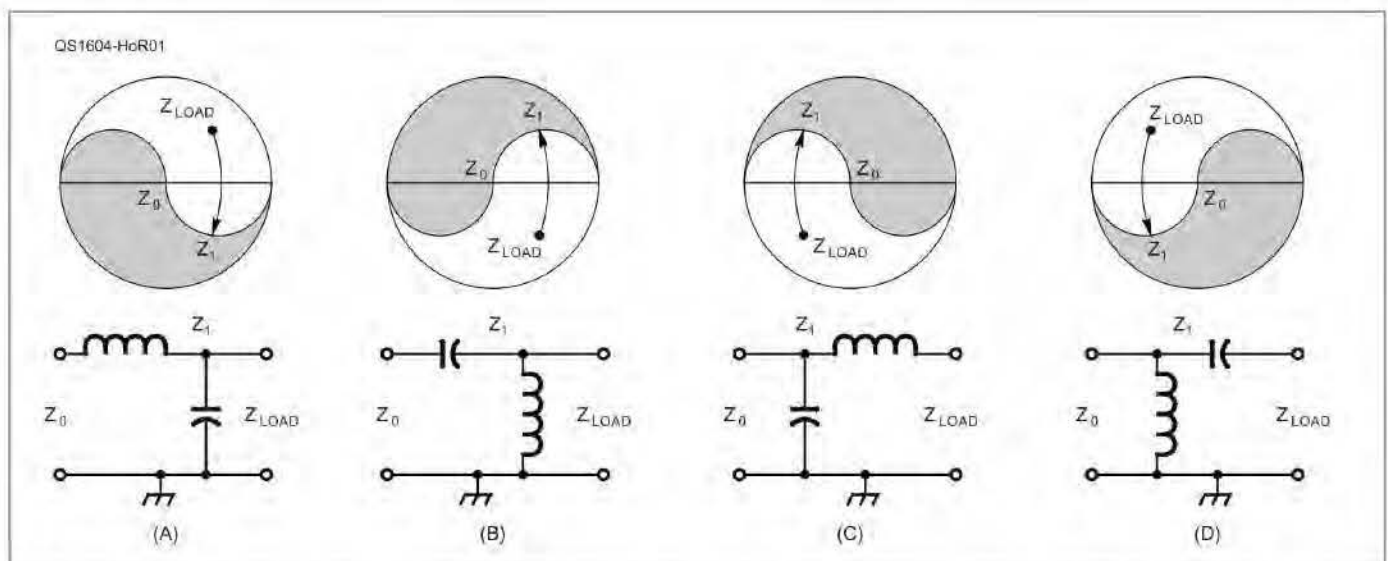


Figure 4 — The four types of L-C networks and the regions on the Smith chart representing impedances they can be designed to match.

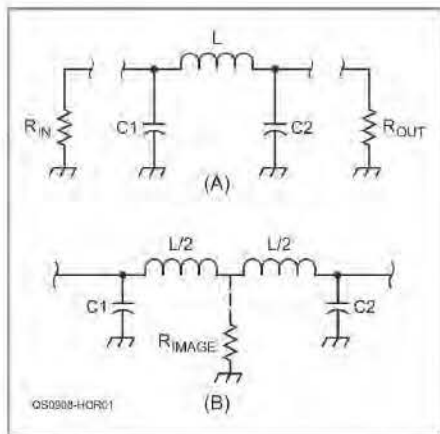


Figure 5 — Electrically identical to a pair of back-to-back L-networks, the Pi-network provides wider matching bandwidth than a single L-network.

That means if you can't adjust an L-network for a match with a particular load impedance, turn it around!

Pi-networks

A drawback of the L-network is the bandwidth over which it matches gets narrower as the difference between the input and output impedances increases. The "Q" of the network also increases, meaning voltages and currents in the components will be higher, increasing losses (and expense). The Pi-network is one answer.

As shown in Figure 5, you can think of the Pi-network as two L-networks back to back.^{9, 10} This is like using an idler gear to change speed in smaller steps. The result is a wider bandwidth and less stress on the L and C components.

The Pi-network is most often used in tube amplifiers where a tube's internal impedance of more than 1,000 Ω needs to be matched to the antenna system's 50 Ω impedance — a ratio of more than 20:1. The Pi-network's wider bandwidth means less tuning across a band and less expensive components. The most common configuration uses a series inductor, making it a *low-pass network* that provides additional *harmonic attenuation*.

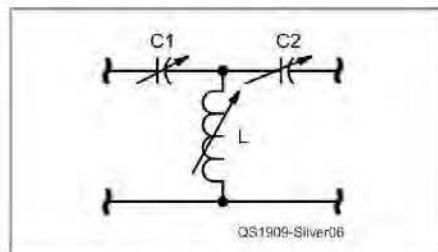


Figure 6 — The T-network can also be thought of as a pair of back-to-back L-networks. Change L to a pair of inductors in parallel, each with a value of 2L.

T-networks

The T-network in Figure 6 is also equivalent to a pair of back-to-back L-networks. Instead of splitting the series inductor into two, the inductor L is changed to a pair of inductors in parallel, each with a value of 2L.

This is the circuit for most antenna tuners sold commercially and it has an extremely wide range of impedances that it can match.¹¹ This configuration is a *high-pass network* because of the series capacitors between the input and the output, so no additional harmonic suppression is provided. The high-pass configuration is less expensive to build, as well.

Other Impedance Matching Techniques

While this article covers only *passive* or unpowered circuits, *active* circuits can be used to convert impedances, too. The common-emitter (or common-source) and common-base (or common-gate) amplifiers act as impedance converters that also increase signal power.^{12, 13} Op-amp circuits perform similar conversions, as well. In the upcoming article, we'll take a look at how transmission lines work their magic and reflect on the various ways of using them.

Notes

- ¹ *The ARRL Antenna Book*, 23rd Edition, ch. 24, "Transmission Line System Techniques." Available from your ARRL dealer or the ARRL Bookstore, ARRL Item no. 0444. Telephone 860-594-0355, or toll-free in the US 888-277-5289; www.arrl.org/shop; pubsales@arrl.org.

² *The ARRL Handbook for Radio Communications*, 2019 Edition, ch. 22, Reference Tables, "Component Data and References." Available from your ARRL dealer or the ARRL Bookstore, ARRL Item no. 0888. Telephone 860-594-0355, or toll-free in the US 888-277-5289;

www.arrl.org/shop; pubsales@arrl.org.

³ "Hands-On Radio #94 — SWR and Transmission Line Loss," available to ARRL members at www.arrl.org/hands-on-radio.

⁴ *The ARRL Handbook for Radio Communications*, ch. 5, "RF Techniques."

⁵ G. Grammer, W1DF, "Simplified Design of Matching Networks, Parts 1 — 3," *QST*, Mar./Apr./May, 1957.

⁶ "Hands-On Radio #21 — The L-Network," www.arrl.org/hands-on-radio.

⁷ "Hands-On Radio #59, #60, #61 — Smith Chart Fun," www.arrl.org/hands-on-radio.

⁸ "Hands-On Radio #157 — Matching — Network Design and Build," www.arrl.org/hands-on-radio.

⁹ "Hands-On Radio #159 — More L Network Design," www.arrl.org/hands-on-radio.

¹⁰ "Hands-On Radio #79 — Pi and T Networks," www.arrl.org/hands-on-radio.

¹¹ J. Hallas, W1ZR, *The ARRL Guide to Antenna Tuners*. Available from your ARRL dealer or the ARRL Bookstore, ARRL Item no. 0984. Telephone 860-594-0355, or toll-free in the US 888-277-5289; www.arrl.org/shop; pubsales@arrl.org.

¹² "Hands-On Radio #1 — The Emitter-Follower Amplifier," www.arrl.org/hands-on-radio.

¹³ "Hands-On Radio #28 — The Common-Base Amplifier," www.arrl.org/hands-on-radio.

Ward Silver, N0AX, has been licensed since 1972. He is Lead Editor of *The ARRL Handbook* and *The ARRL Antenna Book*, and is the author of all three editions of the *ARRL Ham Radio License Manual* and study guides. He released the well-received *Grounding and Bonding for the Radio Amateur* in 2017 and recently authored the third edition of *Ham Radio for Dummies*. An electrical engineer, Ward designed microprocessor-based products and medical devices for 20 years before beginning a second career as a teacher and writer. He is a cofounder of the World Radiosport Team Championships, was inducted into the CQ Contest Hall of Fame in 2015, and is President of the Yasm Foundation. You can contact Ward at n0ax@arrl.org.

For updates to this article, see the QST Feedback page at www.arrl.org/feedback.

